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Patentanmeldung Nr. | Patent application No. | Demande de brevet n°

03000358.6

PRIORITY DOCUMENT

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R C van Dijk

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Application no.: 03000358.6
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SUISSE

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A fast and parallel single photon counting device for single x-ray counting

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Description

A fast and parallel single photon counting device for single x-ray counting

The invention relates to a photon-counting imaging device for single x-ray counting.

X-ray diffraction patterns are useful in the analysis of molecular structures, such as protein and virus molecules, and require photon counting imaging devices. Especially, protein and virus crystallography imposes stringent requirements on x-ray detectors, particularly where the x-ray source is high flux synchrotron radiation that enables an experiment to be done rapidly. Furthermore, an important and developing field is time-resolved diffraction experiments using synchrotron radiation, such as crystallography and/or powder diffraction analysis. Monitoring a time-dependent reaction in a sample, i.e. a crystal or a powder, can elucidate the time-dependent crystal/molecular changes that occur in a chemical reaction as well. High time resolution speed is often critical in such monitoring.

In the literature, a high speed crystallography detector is disclosed by the US patent 5,629,524 and a solid-state image sensor with focal-plane digital photon-counting pixel array is disclosed by the US patent 5,665,959. The latter patent describes and illustrates a focal-plane array comprising an array of NxN photodetector diodes connected to a digital photon-counting means for ultralow level image light detection and digital image pixel readout means for each pixel comprising separate CMOS buffer amplifiers that exhibit the following characteristics: low power (< 1 μW per pixel average), high photoelectron charge to voltage conversion

gain (≈ 1 mV/e⁻), low noise (< 1 e⁻), small cell pitch (< 30 µm), easy scalability (to 10 µm), self biasing capability, sufficient gain uniformity (~ 10%) for multiple event discrimination, and bias current programmability. Any incident photon during the sampling period generates a photoelectron at the output of the detector diode connected to the input of the amplifier. That photoelectron changes the potential of the buffer amplifier's input capacitance. This chance in potential causes the high-gain buffer amplifier to present a sufficiently large voltage change at the output of the amplifier to be above the system noise level.

The drawback of this disclosure remains substantially in the design of this photon counting device that is dedicated to detect with brilliant sensitivity a single photon having its energy in the range of the visible light (several eV). This device can therefore be used for infra-red binoculars or for space-based telescopes and spectrometers. The electronic circuitry is therefore that sensitive that an incident photon is amplified in order to saturate the buffer of the amplifier. An additional incident photon occurring in the same photodetector diode in the same sampling period as the first incident photon therefore can not be detected unless the buffer is reseted. This photon detecting device is therefore completely useless for the above-mentioned purposes of x-ray photon detection.

Nevertheless, the general desing of the semiconductor chip is preferably a hybrid using a separate semiconductor material for two chips selected to be optimum for the photovoltaic type of detector diodes in one and the buffer amplifier and multiplexing circuit in the other chip bump bonded to the first to make connections between the output interface of the detector diodes on one chip and the input interface of the buffer amplifier on the other chip with the photodetector diodes buffer amplifier in one semiconductor chip and the multiplexing means and digital counters on the second

semiconductor chip bump bonded to the first one of the hybrid: As disclosed in the US patent 5,629,524 a suitable ~~material for the electrical bump connection is Indium.~~ But even this device for x-ray photon detection can not be used in high dynamic investigation since the electronic circuitry is limited due to the switching dead time that is required to integrate the charge of the photo electrons subsequently to a chain of capacitors (referred to as a M-bit shift register) which have to be read out afterwards serially due to its chain-like arrangement. It could be easily understood that the performance of this circuitry is limited to its switching intervals charging and scanning the capacitors.

Another prior art document worth to be mentioned is the US patent No. 5,812,191 disclosing a semiconductor high-energy radiation imaging device having an array of pixel cells including a semiconductor detector substrate and a semiconductor readout substrate. The semiconductor detector substrate includes an array of pixel detector cells, each of which directly generates charge in response to incident high-energy radiation. The semiconductor readout substrate includes an array of individually addressable pixel circuits, each of which is connected to a corresponding pixel detector cell to form a pixel cell. Each pixel circuit includes charge accumulation circuitry for accumulating charge directly resulting from high-energy radiation incident on a corresponding pixel detector cell, readout circuitry for reading the accumulated charge, and reset circuitry for resetting the charge accumulation circuitry. Unfortunately, the accumulated charge is stored as analog data using a circuitry having two transistors, one transistor acting as the charge store while the other acts as a readout switch responsive to an enable signal. This design restricts the circuitry to allow individual addressing each pixel but only discharge the accumulated analog charge to an output line when activated by its respective enable signal. This

circuitry does not enable any further manipulation of the pixel detector cells.

Another imaging device for imaging radiation according to the international patent application WO 98/16853 includes an image cell array. The image cell array includes an array of detectors cells which generates charge in response to instant radiation and an array of image cell circuits. Each image cell circuit is associated with a respective detector cell. The image cell circuit includes counting circuitry for counting plural radiation hits incident on an associated detector cell. Preferably, the image cell circuit includes threshold circuitry connected to receive signals generated in the associated detector cell and having values dependent on the incident radiation energy. The counting circuitry is then connected to the threshold circuitry for counting only radiation hits within a predetermined energy range or ranges. The electronic readout circuitry is designed to comprise a loadable shift register storing the data serially in a row that means the input data is the data from the previous pixel and the output delivers the actual data to the next pixel. The main drawback of this arrangement consists in the susceptibility to a failure of a complete row of the detector array if only one the readout circuitry in a row fails.

Resuming the prior art document it will be apparent that none of the document disclose a photon counting imaging device that allow high readout performance und superior reliability of operation.

Therefore, it is the aim of the invention to increase the performance and the reliability of a complete photon-counting imaging device.

This aim is achieved according to the invention by a photon-counting imaging device for single x-ray counting comprising:

a) a layer of photosensitive material (4);

b) a source of bias potential (12);

c) a source of threshold voltage supply (U_T);

d) an NxM array of photodetector diodes (2) arranged in said layer of photosensitive material (4); each of said photodetector diodes (2) having a bias potential interface and a diode output interface (20), said bias potential interface of each photodetector diode (2) being connected to said bias potential (12);

e) an NxM array of high gain, low noise readout unit cells (18, 36), one readout unit cell (18, 36) for each photodetector diode (2);

f) each readout unit cell (18, 36) comprising an input interface (22) connected to said diode output interface (22), a high-gain voltage amplifying means (46) comprising a comparator unit (CA), a digital counter unit (48), comprising a digital counter (RSC), and a digital counter output interface (RBO) connected in series, each digital counter unit (48) counting an output signal of the comparator unit (CA); said output signal is proportional to a number of electron/hole pairs (10) generated by a photon (6) in the respective photodetector diode (2),

g) a multiplexing means (MM) comprising a row select (RS) and a column select (CS) allowing to access each of the readout cell units, i.e. to read out the digital data as actually stored in the digital counter (RSC) to the digital counter output interface;

h) each digital counter output interface (RBO) connected to an output bus

i) said output bus being connected to a data processing means (DPM) controlling the multiplexing means (MM).

According the these measures, a photon counting imaging device is created having an architecture of the readout circuitry that allows to be tolerant with respect to a local defect of a detector diode and/or readout unit cell and that

allow to control and redesign the program and/or the status of each detector diode and/or readout unit cell.

An advantageous architecture comprises the diode output interface of the photodetector diodes and the input interface of the readout unit cell to be connected to each other by bump bonding, preferably using indium bumps for the bump bonding. This measure facilitates the manufacturing of a photodetector diode and readout cell unit assembly at considerably low temperatures. Using the indium bumps leads in detail to soldering temperatures lower than 100°C that not jeopardizes the fine structures of the complete assembly.

To allow control and access to each of the readout unit cells and/or detector diodes the data processing means are provided being connected via the multiplexer means to said array of readout unit cells. Therefore, two independent shift register of the multiplexing means can access the circuitry of one pixel by electing the respective pixel via row and column select. To interact with the data processing means each readout unit cell comprises an AND-gate having as inputs the row select and the column select of the multiplexing means. If both inputs are high the AND-gate set high and access to the readout unit cell is established.

Another favourable feature in developing the afore-mentioned invention can provide said data processing means controlling a enable/disenable switch being comprised in said high gain voltage amplifying means, preferably in the comparator unit. Therefore, the data processing means control said enable/disenable switch in order to trigger temporarily the gate of an amplifying means being comprised in said high gain voltage amplifying means.

In order to globally or individually adjust a proper sensisitivity of all or only of an individual detector diode said source of threshold voltage supply to said high-gain

voltage amplifying means comprises an adjustable source of threshold voltage correction supply, both being controlled by the data processing means via the multiplexer means.

A consequential measure provides the data processing means to control via the multiplexing means one or more of the following issues:

a) programming of the readout unit cell via a port (DIN);
b) readout of the data in the readout unit cell via a port (DOUT);
c) calibration of the readout unit cell, preferably the high gain voltage amplifier means (46), via a port (CAL); and
d) analyzing the analog signal in the high gain voltage amplifier means (46) for the purpose of diagnosis via a port (AOUT).

This measure now in detail explains the advantages derivable from the afore-mentioned multiplexing means that allow the direct access to each readout unit cell. The calibration in the regard is considered to be able to calibrate the bias of each photodetector diode. Another calibration can be achieve by the afore-mentioned adjustment of the threshold voltage by the threshold voltage correction supply. For evaluating the status of the photodetector diode and/or the analog part of the readout unit cell circuitry in detail the analysis of the analog signal processed with the high gain voltage amplifier means is very helpful and could only be achieved by the ability to address a distinct detector pixel using two independent row and coloumn address registers of the multiplexing means.

For constructing a photon-counting imaging device detecting the photon radiation over a comparably large focal or flat area a suitable architecture can provide said NxM array of photodetector diodes, said NxM array of said readout unit cells being arranged on a first substantially flat support plate for building a sensor module, and a sensor module

control board being arranged on a second substantially flat support plate; said first substantially flat support plate and said second substantially flat support plate being arranged under an angle to each other. A suitable angle may reside within a range of 30 to 120°, preferably 45 to 100°. This measure allows to construct a plane or curved detector surface area made from a number of sensor modules having stretched out on the opposite side of its detector surface the sensor module control board comprising at least partial the required readout electronic equipment, i.e. the data processing means or at least part of them.

For forming a large solid-state photon-counting imaging device a number of the afore-mentioned sensor modules being arranged in a substantially flat or curved VxW array wherein V and W are integer numbers at least one of them larger than one.

Examples of the invention are described below in accordance with the drawings which depict:

Figure 1 a schematic view of a photodetector diode;

Figure 2 a schematic view of a part of a sensor module comprising an array of photodetector diodes as one shown in Figure 1;

Figure 3 a schematic view of a microstrip detector;

Figure 4 a schematic view of the readout electronic of a readout unit cell assigned to and connected with a photodetector diode as shown in Figur 1;

Figure 5 a sensor module as a basic element for a photon-counting imaging device having a number of those sensor modules with a sensor module control board; and

Figure 6 a schematic view on a sensor module readout process.

Figures 1 illustrates schematically the architecture of a photodetector diode 2 having a doped semiconductor p^+, n^+, n^{++} trespassing section 4. The material choosen for the photodetector diode 2 depends on the desired bandgap energy required to generate an electron hole pair by the photo-effect. Suitable materials are undoped amorphous silicon having band gap of 1.12 eV and a bundle of IV-IV compounds and III-V compounds (indium and gallium salts, like gallium arsenide or indium antimonide).

An incident photon 6 having an energy in the rage of several KeV before entering the doped semiconductor p^+, n^+, n^{++} trespassing section 4 passes through an aluminium cover layer 8 and causes according to its energy and to the energy gap of the doped semiconductor p^+, n^+, n^{++} trespassing section a respective number of electron hole pairs 10 under x-ray annihilation. In the drawing this number of electron hole pairs is exemplarily shown by one electron-hole pair 10 being divided by the voltage generated by a source of bias potential 12. The evaluation of the charge occurred from the electron hole pairs 10 will be described below with reference to figure 4.

Figure 2 shows a schematical view of a two-dimensional pixel detector 14 having a number of photodetector diodes 2 arranged in an array of 22 rows and 32 columns (compare figure 6).The photodetector diodes 2 have a length l and a width w of about 200 µm and a height of about 300 µm. Below the plane of these photodetector diodes 2 a readout chip 16 having a corresponding number of readout cell units 18 is arranged for collecting the charge from the electron hole pairs 10 generated in the respective photodetector diodes 2. The electrical conjunction between a diode output interface

20 of the photodetector diodes 2 and an input interface 22 of the readout cell units 18 is achieved by bump bonding using indium bumps 24.

Figure 3 depicts a schematical view of a microstrip detector 26 having on a hybrid support 28 arranged a number of thirty-eight strip-type photodetector diodes 30 build in a microstrip sensor sector 32 of the hybrid support 28. The strip-type photodetector diodes 30 have a width of about 15 µm, a length of about 8 mm and a pitch of about 50 µm. Next to the microstrip sensor sector 32 a microstrip readout sector 34 is arranged having a number of readout cell unit 36 (not shown in detail) corresponding to the number of strip-type photodetector diodes 30. These readout cell units 36 are connected with their input interface 22 to the photodetector diodes 30 by bond pads 38 which additionally connect an output interface 40 of the readout cell units 36 to a digital counting sector 42 which is described below, too.

Figur 4 now depict a schematic view of a electronic readout equipment 44 as it can be used for both the two-dimensional pixel detector 14 and the microstrip detector 26. The electronic readout equipment 44 is divided into an analog block 46 and a digital block 48. The analog block 46 starts with the bump pad 18, 38 resp. connected to an input terminal of a cascade-style amplifier Amp. For calibration purposes a source for calibration voltage U_{Cal} is connected via a capacitor C to the input terminal of the CS amplifier Amp, too. The capacity of the capacitor has been chosen to a comparably tiny capacity of about only 1.7 fF allowing to be sensitive enough that the photo-electrons can change the voltage over the capacitor C to an extend that this difference can be significantly amplified by the CS amplifier Amp hereinafter referred to as first output voltage signal.

This first output voltage signal is led to one of the two input terminals of a comparator amplifier CA which is

additionally connected to a source of a threshold voltage supply U_T. The other input terminal of the comparator amplifier CA is additionally connected to a source of threshold voltage correction supply TC. This source of threshold voltage correction supply TC allows to bias the input terminals of the comparator amplifier CA. According to the predetermined bias of the input terminals of the comparator amplifier CA even the first output voltage signal from the CS amplifier Amp representing only a fractional part of the charge of the generated photo-electron hole pairs can be further processed and is therefore not supressed. This electronic readout equipment 44 enables the detection of fractions of the full charge of a the photo-electron hole pairs 10 generated by an incident x-ray what may occur when the photo-electron hole pairs 10 are generated in the twilight zone located between two adjacent photodetector diodes 2.

As an example, the source of threshold voltage correction supply TC can be adjusted to a level defined by one half of the full charge of the photo-electron hole pairs 10 generated in total by one x-ray photon. Consequentially, the distribution of the charge of the photo-electrons to adjacent photodetector diodes 2 can be further processed. A downstream data processing unit is now enabled to perform a differential evaluation of the digital output voltage signals of the comparators having its origin from the photo-electrons in adjacent photodetector diodes 2, whereby these photo-electrons have been generated by the same x-ray photon.

Downstream to the analog block 46 is the digital block 48 having generally the task to convert the digital output voltage signal into a digital counter signal that can be evaluated by multiplexing means MM provided with the a data processing means DPM. Together with a enable/disenable switch E/D different clock means, i.e. an external clock RCLK from the data processing means DPM control a clock generator CG

for a digital counter unit SRC which itself is connected to a readout bus output RBO. The digital data stored in the digital block 48 of a distinct readout unit cell can then be readout if a row select RS and column select CS are set high to set high an AND-gate &.

Figure 5 illustrates a solid-state photon-counting imaging device 50 detecting the photon radiation over a comparably large flat area. The present architecture combine a number of sixteen pixel sensors 14 being arranged on a first substantially flat support plate 52 for building a sensor module 54, and a sensor module control board 56 being arranged on a second substantially flat support plate 58 hosting the electronic evaluation equipment, i.e. multiplexing means MM, data processing means DPM, which follow the afore-mentioned electronic readout equipment 44. The first substantially flat support plate 52 and the second substantially flat support plate 58 being arranged under an angle of 90°. This measure allows to construct a plane or curved detector surface area (here not shown in the drawings) made from a number of sensor modules 54 having stretched out on the opposite side of its detector surface the sensor module control boards 56.

Figure 6 now shows a schematic view on a sensor module readout process indicating that appropriate multiplexing means MM allowing with a row select logic RS and a column select logic CS to address a predetermined readout cell unit 18 in order to readout the value of the digital counter SRC. This addressability lead to the capability of the complete photon-counting imaging device 50 to access and/or control continiously or temporarily each readout cell unit. The photon-counting imaging device (50) owns the capability to access and/or control via the data processing means (DPM) via the multiplexing means (MM) one or more of the following issues:

a) programming of the readout unit cell via a port (DIN);

b) readout of the data in the readout unit cell via a port (DOUT);

c) calibration of the readout unit cell, preferably the high gain voltage amplifier means (46), via a port (CAL); and

d) analyzing the analog signal in the high gain voltage amplifier means (46) for the purpose of diagnosis via a port (AOUT).

All the afore-mentioned ports DIN, DOUT, CAL and AOUT are comprised in the readout bus RB that is controlled by the data processing means DPM. The described issues especially allow to access certain regions of interest that yield a much higher readout frequency owing to the fact that only the selected readout cell units 18 and their assigned digital counter values have to be addressed. According to a respective programing of the multiplexing means and the data processing means this feature can encourage the solid-state photon-counting imaging device 50 to generate itself said regions of interest due to the measured amounts of photons in the respective photodetector diodes 2 or due to stored clusters of an expected occurrence of a photon distribution profile. Therefore, the dynamic rollout of material hardening processes or generally processes under which changes in the crystal structure of the investigated material take place can be observed with a comparably high time resolution.

List of reference number

2	Photodetector diode
4	Doped semiconductor p^+, n^+, n^{++} trespassing section
6	Photon
8	Aluminium cover layer
10	Electron hole pair
12	Source of bias potential
14	Pixel detector
16	Readout chip
18	Readout cell units
20	Diode output interface
22	Input interface
24	Indium bumps
26	Microstrip detector
28	Hybrid support
30	Strip-type photodetector diodes
32	Microstrip sensor sector
34	Microstrip readout sector
36	Readout cell units
38	Bond pads
40	Output interface
42	Digital counter section
44	Electronic readout equipment
46	Analog block
48	Digital block
50	Solid-state photon-counting imaging device
52	First substantially flat support plate
54	Sensor module
56	Sensor module control board
58	Second substantially flat support plate
Amp	Cascade-style Amplifier
C	Capacitor
CA	Comparator amplifier
CG	Clock generator
CS	Column select

E/D	Enable/Disenable Switch
MM	Multiplexing Means
RB	Readout bus
Reset	Digital counter reset
RS	Row select
SRC	Digital counter unit
TC	Source for threshold voltage correction supply
U_{Cal}	Source for calibration voltage
U_T	Source for threshold voltage supply

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Patent Claims

1. A photon-counting imaging device (50) for single x-ray counting comprising:
   a) a layer of photosensitive material (4);
   b) a source of bias potential (12);
   c) a source of threshold voltage supply (U_T);
   d) an NxM array of photodetector diodes (2) arranged in said layer of photosensitive material (4); each of said photodetector diodes (2) having a bias potential interface and a diode output interface (20), said bias potential interface of each photodetector diode (2) being connected to said bias potential (12);
   e) an NxM array of high gain, low noise readout unit cells (18, 36), one readout unit cell (18, 36) for each photodetector diode (2);
   f) each readout unit cell (18, 36) comprising an input interface (22) connected to said diode output interface (22), a high-gain voltage amplifying means (46) comprising a comparator unit (CA), a digital counter unit (48), comprising a digital counter (RSC), and a digital counter output interface (RBO) connected in series, each digital counter unit (48) counting an output signal of the comparator unit (CA); said output signal is proportional to a number of electron/hole pairs (10) generated by a photon (6) in the respective photodetector diode (2),
   g) a multiplexing means (MM) comprising a row select (RS) and a column select (CS) circuit allowing to access each readout cell unit, i.e. to read out the digital data as actually stored in the digital counter (RSC) to the digital counter output interface;

h) each digital counter output interface (RBO) connected to an output bus

i) said output bus being connected to a data processing means (DPM) controlling the multiplexing means (MM).

2. The photon-counting imaging device (50) according to claim 1, characterized in that
the diode output interface (20) of the photodetector diodes (2) and the input interface (22) of the readout unit cell (18, 36) are connected to each other by bump bonding.

3. The photon-counting imaging device (50) according to claim 2, characterized in that
indium bumps (24) are used for the bump bonding.

4. The photon-counting imaging device (50) according to any one of the preceeding claims, characterized in that
the data processing means (DPM) are provided being connected via the multiplexer means (MM) to said array of readout unit cells (18, 36) allowing to control each of the readout unit cells (18, 36).

5. The photon-counting imaging device (50) according to claim 4, characterized in that
said data processing means (DPM) controls a enable/disenable switch (E/D) being comprised in said high gain voltage amplifying means (46), preferably in the comparator unit (CA).

6. The photon-counting imaging device (50) according to any one of the preceding claims, characterized in that
said source of threshold voltage supply (U_T) to said high-gain voltage amplifying means (46) comprises an adjustable source of threshold voltage correction supply (TC), both being controlled by the data processing means (DPM) via the multiplexer means (MM).

7. The photon-counting imaging device (50) according to any one of the preceding claims, characterized in that the data processing means (DPM) control via the multiplexing means (MM) one or more of the following issues:

a) programming of the readout unit cell via a port (DIN);
b) readout of the data in the readout unit cell via a port (DOUT);
c) calibration of the readout unit cell, preferably the high gain voltage amplifier means (46), via a port (CAL); and
d) analyzing the analog signal in the high gain voltage amplifier means (46) for the purpose of diagnosis via a port (AOUT).

8. The photon-counting imaging device (50) according to claim 1, characterized in that said NxM array of photodetector diodes (2), said NxM array of said readout unit cells (18, 36) being arranged on a first substantially flat support plate (52) for building a sensor module (54), and a sensor module control board (56) being arranged on a second substantially flat support plate (58); said first substantially flat support plate (52) and said second substantially flat support plate (58) being arranged under an angle (α) to each other.

9. The photon-counting imaging device (50) according to claim 8, characterized in that said angle (α) is in a range of 30 to 120°, preferably substantially 45 to 100°.

10. The photon-counting imaging device (50) according to claim 9 or 10, characterized in that a number of said sensor modules (54) being arranged in a substantially flat VxW array.

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A photon-counting imaging device (50) for single X-ray counting is disclosed comprising:

a) an NxM array of photodetector diodes (2) arranged in said layer of photosensitive material (4); each of said photodetector diodes (2) having a bias potential;
b) an NxM array of high gain, low noise readout unit cells (18, 36), one readout unit cell (18, 36) for each photodetector diode (2);
c) each readout unit cell (18, 36) comprising a high-gain voltage amplifying means (46) comprising a comparator unit (CA), a digital counter unit (48) and a digital counter output interface (RBO) connected in series,
d) a multiplexing means (MM) comprising a row select (RS) and a column select (CS) logically connected to an AND-gate, said AND-gate is provided for each readout unit cell and said AND-gate in its activated status allowing to read out the digital data as actually stored in the digital counter (RSC) to the digital counter output interface;
e) each digital counter output interface connected to an output bus (RB)
f) said output bus (RB) being connected to a data processing means (DPM) which controls the operation of the multiplexing means (MM).

According to these measures, a photon counting imaging device is created having an architecture of the readout circuitry that allows to be tolerant with respect to a local defect of a detector diode and/or readout unit cell and that allow to control and redesign the program and/or the status of each detector diode and/or readout unit cell. In addition, it allows a selective and fast readout of a region of interest (ROI) for time resolved studies.

Fig. 5

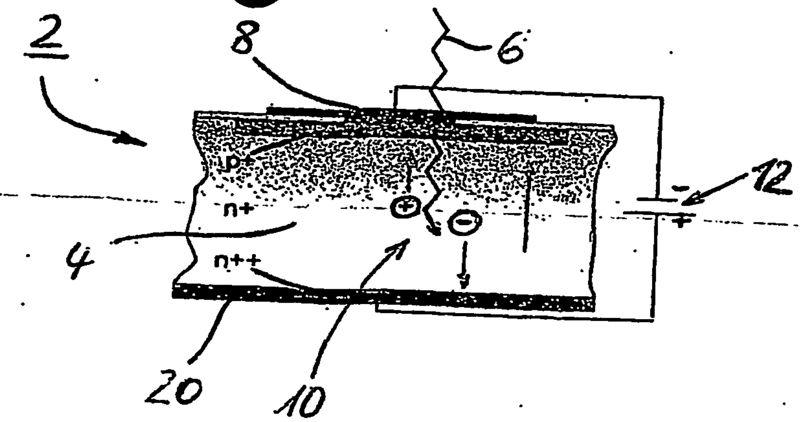


Fig. 1

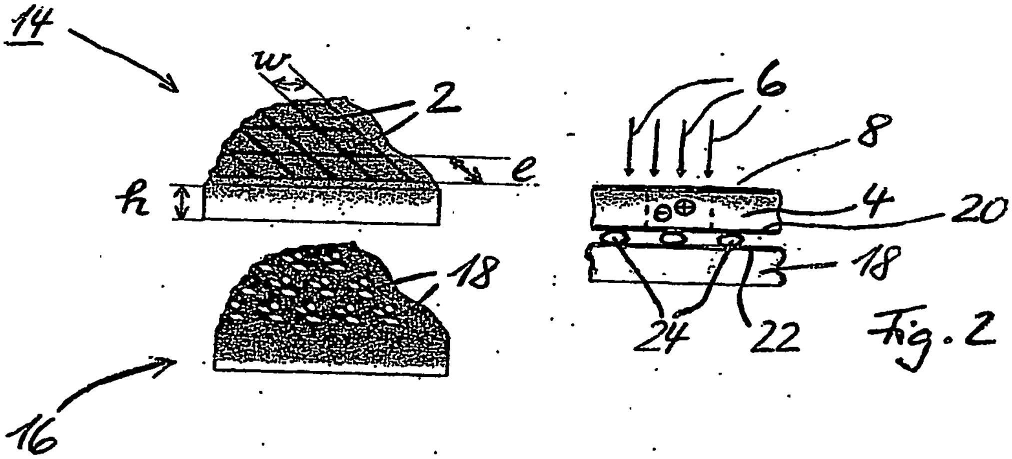


Fig. 2

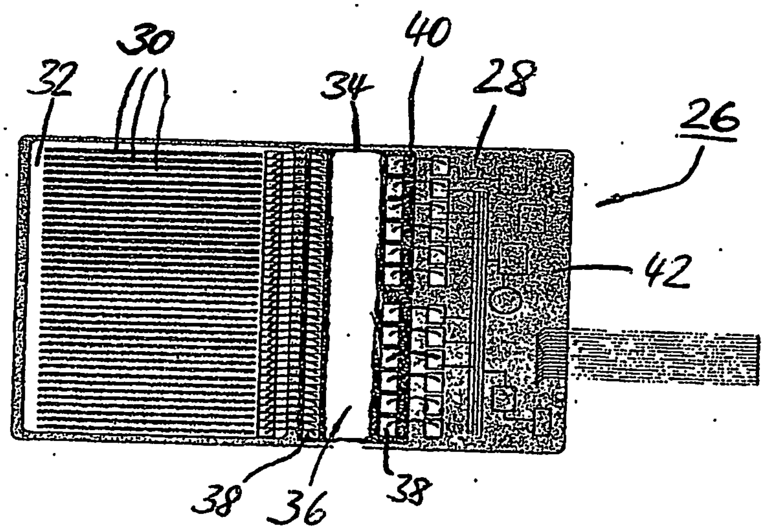


Fig. 3

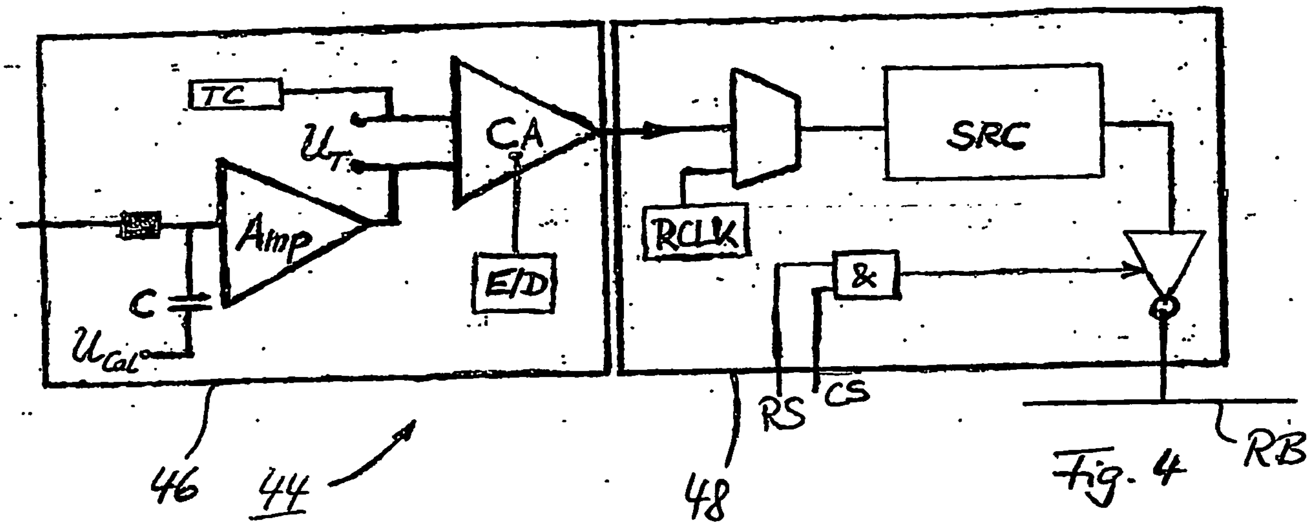


Fig. 4

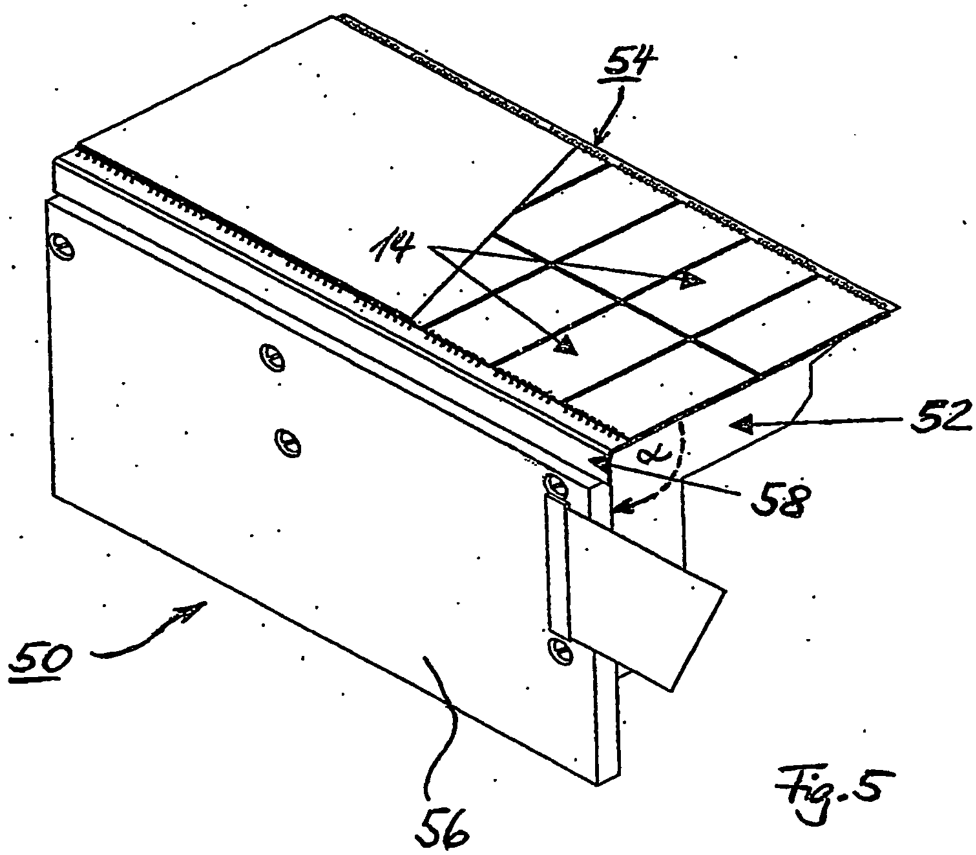
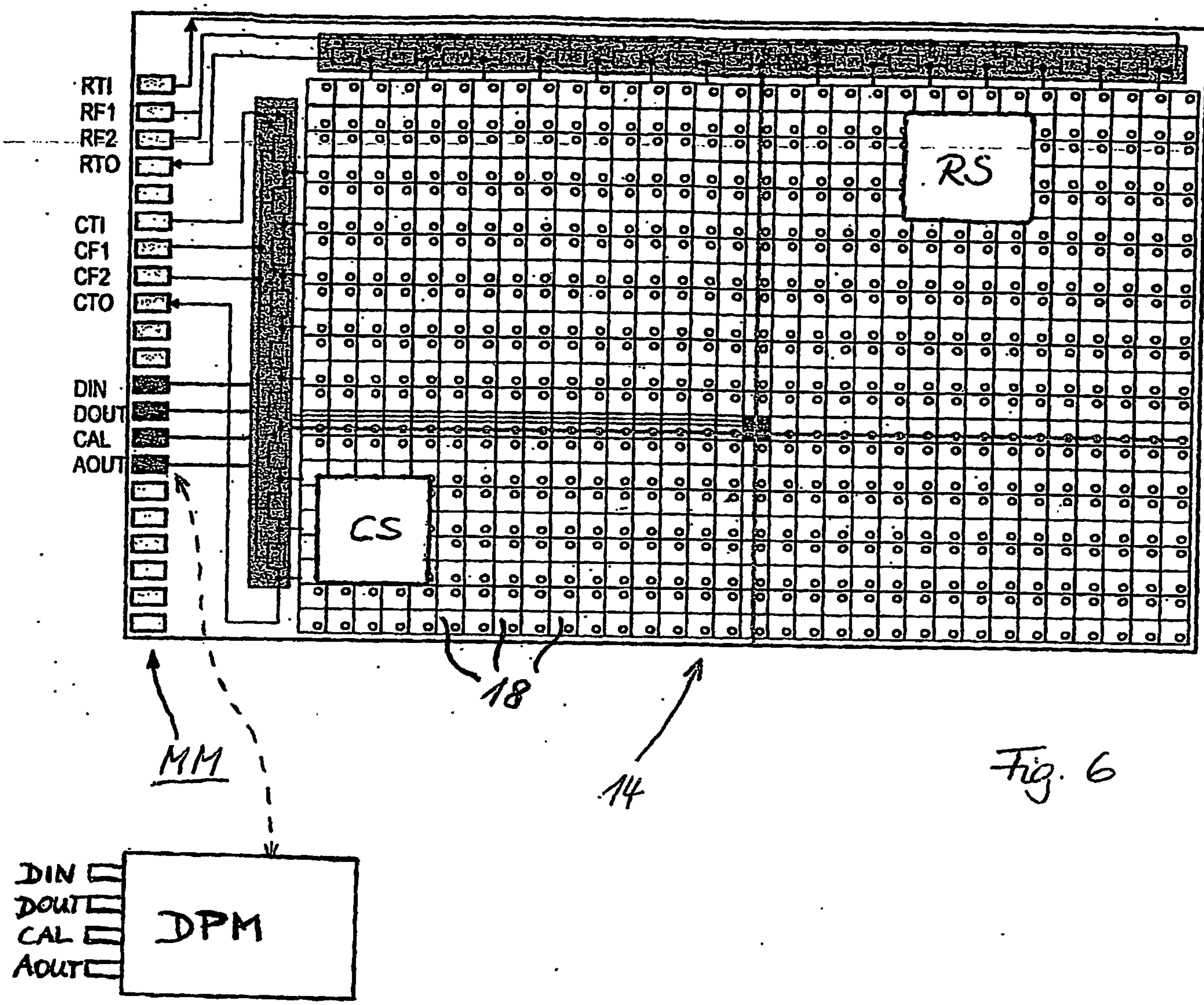


Fig. 5



RTI
RF1
RF2
RTO
CTI
CF1
CF2
CTO
DIN
DOUT
CAL
AOUT
RS
CS
18
14
MM
DIN
DOUT
CAL
AOUT
DPM

Fig. 6